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against the thermal hazards of electric fault arcs***

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### Risk analysis and guidelines for selecting PPE against the thermal hazards of electric fault arcs

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#### Abstract

Electric fault arcs occurring with short-circuits in electric power equipment and installations are enormous sources of power. There are particularly thermal effects (radiation and convective heat flux, metal splash) with high risks for persons especially in case of direct exposure, e.g. during live working or working in the vicinity of live parts. Personal protective equipment (PPE) can essentially contribute to increase the personal safety.

The selection of protective measures or the assessment of their efficiency requires a risk analysis. Since the thermal arc hazards are proportional to the electric arc energy as well as the incident energy in the exposure distance, the risk assessment has to be based on the energy conditions. The electric arc energies to be expected in the electric power systems (working places) under consideration have to be determined as well as the equivalent energetic protection levels of the PPE.

The paper gives an algorithm for analyzing the thermal arc risks for finding the necessary protection class of PPE according to the box test levels for protective clothing (IEC or EN 61482-1-2). Interconnections to the influence of the electric protection devices are shown.

**Key words:** live working, arc flash protection, risk analysis, personal protective equipment, protection levels

#### 1. Introduction

In case of fault arcs occurring with short-circuits in electric power installations huge amounts of energy are converted and set free. There is the risk of personal injury and damages of the equipment, the electric power supply may be interrupted with enormous outage costs. Besides of the pressure rise, light and sound emission, particularly the thermal arc consequences in form of hot metal particles and, mainly, intensive heat flux due to radiation and convection of hot gases are of high risk potentials. If persons and equipment shall be protected efficiently the electric arc energies and/or incident energies have to be limited. There are different protection targets.

Efficient protection measures to be seen in the switchgear construction, the selection of the electrical protection devices and the use of personal protection equipment (PPE) for persons who are likely to be directly exposed to an arc, require a risk assessment with determining the arc energies to be expected in case of accidents and failures where fault arcs can occur.

PPE can essentially contribute to the protection of persons working at open or opened electric power equipment at live parts or near to live parts. They will not protect people in all situations neither completely against all arc hazards nor in each case. But wearing PPE, if meeting protection requirements and tested accordingly, reduces always the degree of personal injury.

In arc personal protection it has generally to be distinguished between a general arc protection and a special arc protection. Furthermore, protective requirements should always be in accordance with the wearing acceptance and comfort of PPE.

A **basic arc protection** is generally necessary and to be provided by the use of according PPE if there is any risk of an electric fault arc and arc exposure in all the working activities (electro-technical work) and working environment. In case that arc-risky working is more often and/or often done at power equipment of higher rating an **increase arc protection** is necessary. On the other hand, in case of special working activities and extreme arc risks and/or equipment rating the certain application must be considered and a conclusion drawn if live working or working at opened equipment is permitted or not, or the PPE have to meet special requirements. The clearing time of protective devices has a important influence in those cases, and can occasionally reduce exposures.

In the box test according to EN 61482-1-2 [1] there are two test levels representing these protection categories: the arc protection class 1 for basic protection and the class 2 for increased protection. The arc protection classes are characterized by different test energy levels describing the thermal arc resistance and protective thresholds (heat attenuation) of the PPE.

In the risk analysis it has to be considered what protection level is necessary for work activities and places. In special cases it is also important to check the protection requirements in detail for the single case of application.

## 2. Hazards due to arcing faults

Electric fault arcs being huge energy sources, the energies converted during an arcing fault at the fault point are in the range of some Megawatts depending on the short-circuit capacity of the electric power system and the clearing time of the protection devices. The temperatures in the arcs can exceed 10,000 °C. Direct consequences of electric fault arcs are

- optical radiation in the overall wave length range
- a pressure wave with high gradient
- melting and vaporization of electrode materials

and following

- intensive light flash
- extreme heat flux
- over pressure, forces on the body, shrapnel
- sound emission
- hot metal particles and splash.

Arcing faults are stochastic processes. As the result, the arc exposures show also random characteristic.

Exposure indices and arc parameters are distributed in variance ranges, they have to be treated and considered statistically.

As shown by field tests and experimental studies the direct and indirect arc consequences generally depend on the

- electric arc energy  $W_{LB}$
- arc active power  $P_{LB}$
- time duration of arcing  $t_{LB}$
- distance to the arc  $a$ .

## 3. Energetic consideration of arcing fault hazards

The main risk for persons results from the thermal arc effects. The thermal exposure parameter is the incident energy characterizing the density of the heat energy at a distance  $a$  from the arc  $E_i$ . Regarding the personal risks it has generally to be distinguished between direct and indirect exposure. In case of direct arc exposure  $E_i$  is the direct exposure energy  $E_{i0}$ . Otherwise, e.g. when wearing PPE, a person is exposed by the transmitted incident energy  $E_{it}$ . The transmitted incident energy is that part of the direct exposure energy that is not attenuated by the PPE and transmits it.

In an arcing fault, a certain part of electric arc active power is converted into thermal power. The thermal power per area unit is the heat flux  $Q$ . During the arc duration  $t_{LB}$  the heat flux results in the incident energy. There is, in principle, a direct proportionality between the electric arc energy  $W_{LB}$  and the incident energy  $E_i$ . The relationship is, however, very complex and sophisticated. The heat transmission function  $f_T$  is nonlinear and depends from a variety of influences:

$$E_{i0} = f_T \cdot W_{LB} \quad \text{with } f_T = f(x_1, x_2, x_3, x_4, x_5, x_6).$$

Main influences are

- $x_1$  – distance  $a$  to the arc axis
- $x_2$  – arc space environment (open arc, box arc, walls, ...)
- $x_3$  – type of electrode configuration (vertical, horizontal, barriers, 2-phase/3-phase, grounded parts)
- $x_4$  – electrode gap  $d$
- $x_5$  – electrode material
- $x_6$  – level of system voltage and current.

These factors determine what type of arc is formed and represent the heat transmission conditions. Furthermore there are thermodynamic influences and responses of gas flow and thermo-chemical processes (e.g. exothermal electrode reactions). The transmitted incident energy is additionally strongly dependent on the PPE transfer characteristics (material reactions).

It is not possible to derive a general transmission function. And it is also impossible to exactly calculate the incident energy on the base of a physical model.

Risk analysis procedures existing in IEEE and NFPA standards (IEEE 1584 [2], NFPA 70E [3]) as well as a number of calculation methods and tools published [4-9] are based on empirical formulae concluded from simplified models and/or fitted by laboratory tests. The equations are oriented to determine the direct exposure incident energy  $E_{i0}$ . There are different cases with equation parameters for several basic applications (such as LV or MV, open arc or arc-in-a-box). Almost all models or parameterizations are based on the assumption of the heat to be only transmitted by radiation. This also applies to the tests made for identifying the formula parameters.

These methods lead to partially extremely large differences in the incident energies calculated. Essential influences, such electrode materials, the form of heat transmission (radiation only, radiation and convection, hot gases, metal vapour,...) were in principle neither taken into consideration in the approaches nor differentiated. In the use is not only problematically to select the appropriate method or exposure category (formula) but also to identify or specify the exposure conditions in the real application case under study.

The incident energy is in fact the exposure parameter but it is practically more useful to base risk analyses on the electric arc energy which is also an arc parameter but having a few influences less. Its statistical variance is smaller and it may be determined with a better accuracy as shown by measurements.

The arc energy is a well defined measure and rating of the specific conditions of the fault location. It is dependent on the electric power system parameters, the construction of the electric power equipment and the clearing time of the protective devices.

The arc energy to be expected in case of arcing results from the power conversion in all arcs engaged in the fault.

$$W_{LB} = \int_0^{t_k} \sum_v u_{LB} \cdot i_{LB} \cdot dt = P_{LB} \cdot t_k$$

It depends on the total arc active power  $P_{LB}$  and the arc duration  $t_{LB}$ . The arc duration is equal to the fault duration  $t_k$  and is determined by the clearing time of the network short-circuit protection devices (or also special electric protective devices installed).

## 4. Determination of arc energy

For risk assessment, both the expectable arc energy levels at the working places under study have to be compared with the arc energy resistance and protection threshold level provided by the protection equipment and means applied (or intended to be applied). It may be proved that the exposures to be expected are not higher than the arc resistance energy levels.

### 4.1 Expected arc energy (exposures)

As mentioned above, the electric arc energy  $W_{LB}$

$$W_{LB} = P_{LB} \cdot t_k$$

depends on the power system conditions, that means on the system short-circuit capacity  $S_k''$  at the fault locations under consideration

$$S_k'' = \sqrt{3} \cdot U_{Nn} \cdot I_{k3p}''$$

and the short-circuit duration  $t_k$  that is determined by the electrical protective devices (clearing time of the breakers, fuses or occasionally special protection devices) and to be derived from the switching characteristics:

$$W_{LB} = k_p \cdot S_k'' \cdot t_k = k_p \cdot \sqrt{3} \cdot U_{rN} \cdot I_{k3}'' \cdot t_k$$

The factor  $k_p$  is the normalized arc power (referenced to the short-circuit capacity)

$$K_p = P_{LB} / S_k''.$$

It is mainly determined by the electric circuit (power system: mains voltage  $U_{Nn}$ , 3-phase prospective short-circuit current  $I_{k3p}''$ , network impedance resistance-to-reactance ratio  $R/X$ ) and the electric power equipment (construction: especially the electrode gap  $d$ ). These complex dependencies become physically apparent in the arc voltage

$$U_B = f(d; I_k''; U_{rN}; R/X).$$

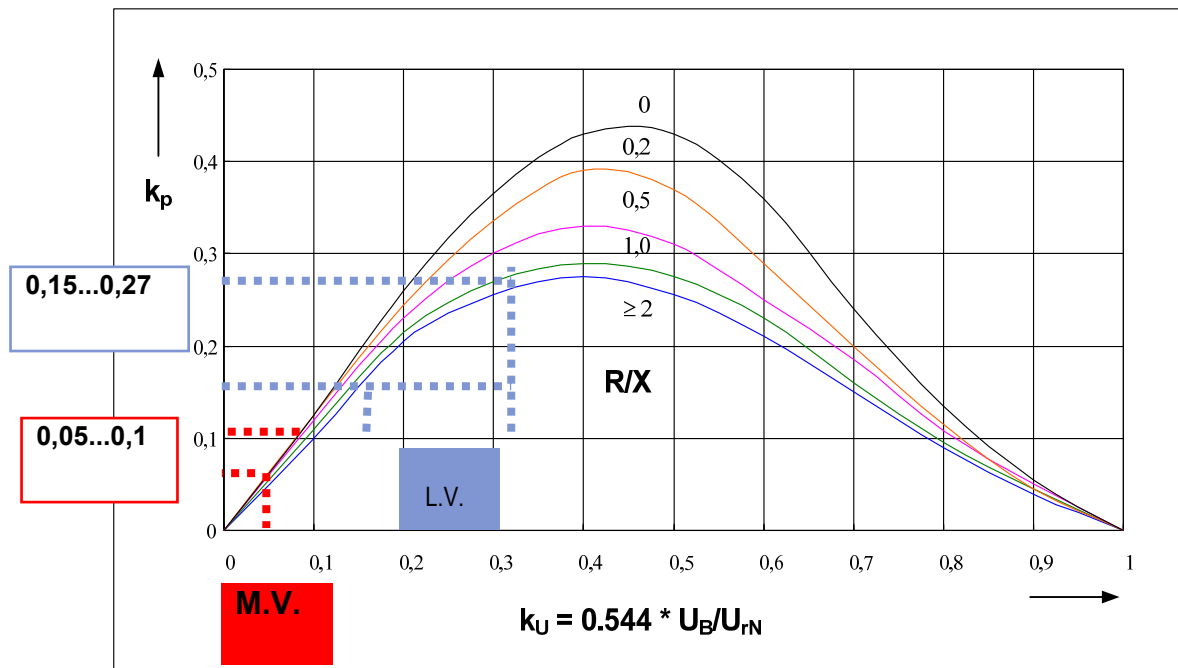
From theoretical considerations the function shown in Fig. 1 was derived for the relationship between normalized arc power and arc voltage [10]. The arc voltage is also normalized and referenced to the system voltage (arc voltage factor  $k_U$ ); the factor 0.544 represents 3-phase short-circuit conditions.

The normalized arc power can approximately be determined from Fig. 1 on the base of the arc voltage  $U_B$ . The electrode spacing is a main influence. According arc voltage values have to be taken from literature, special knowledge is required, among others, regarding the power equipment construction.

For a rough estimation without considering the switchgear geometry the maximum values of the  $k_p$  curves may be used:

$$k_{pmax} = 0,29 \cdot (R/X)^{-0,17}$$

Furthermore the value ranges also given in Fig. 1 were found for a number of usual power installation configurations and may be used as guide values, too. Regarding L.V. systems, these value ranges are mainly typical for power equipment of relatively small conductor spacing.



**Fig. 1:** Normalized arc power in dependency on the arc voltage factor for 3-phase arcing fault

With both, maximum values and guide ones, the practical problems in finding the geometry parameters are avoided at accuracy expenses.

The largest arc energy level determined for the case under study has to be compared with thresholds characterizing the aimed protection target.

## 4.2 Arc resistance and protection energy thresholds

### 4.2.1 Equipment and conditional personal protection for closed electrical installations

It is known from empirical investigations [10] that the arc energy has to be limited in LV switchgear assemblies to about

250 kJ to achieve personal protection outside of a not-opened system

100 kJ to achieve system functional protection (limited post-fault system operation)

under the condition that the installation or switchgear system was tested, and it was proved that the system remains closed after internal arcing. The arc effects and exposures are limited to the inner system.

The conditional personal protection defined here is a limited personal protection presupposing that the power equipment will not be opened for working and service. The protection target system functional protection means that the equipment, if there was internal arcing, can be switched-on and operated again after only eliminating the arcing causes as well as cleaning it and testing its insulating capacity.

### 4.2.2 Personal protection for opened equipment and direct arc exposure

Regarding the thermal hazards of persons due to direct arc exposure when the system is opened (e.g. working near to live parts or live working), the incident energy  $E_i$  is the decisive factor depending on the arc energy, the heat transmission conditions and the exposure distance  $a$ . The heat transfer function for a certain defined scenario of heat transfer and arc exposure includes a distance function  $f(a)$  and a transmission factor  $k_T$  summarizing the special exposure case conditions:

$$E_i = f_T^* \cdot \frac{f(a)}{k_T} \cdot W_{LB}$$

The incident energy occurring at the body surface of a person may not cause 2nd degree skin burns. According physiological thresholds are given by the so-called Stoll criterion [11]. In testing PPE according to the existing internationally harmonized test standards (IEC or EN 61482-1) it is proven that the Stoll threshold is not exceeded. The direct exposure incident energy the PPE is exposed in the test will also not cause thermal damage of the PPE itself.

The consideration of the protective effect of PPE is to be based on the incident energy levels  $E_{i0P}$  which occur in the PPE test. For the box test of protective clothing according to IEC or EN 61482-1-2 these values for the two different arc protection classes 1 and 2 are in fixed correlations to the electric arc energy  $W_{LBP}$  of the test arc prescribed in the standard by the mean values of the validity check ranges. They can be considered as the protection threshold levels of the PPE tested. Tab. 1 gives an overview on these levels statistically verified in a large number of tests. The protection level  $W_{LBP}$  is valid for the heat transmission conditions and the exposure distance of  $a = 300$  mm of the box test set-up.

**Tab. 1:** PPE test and protection levels of arc protection classes

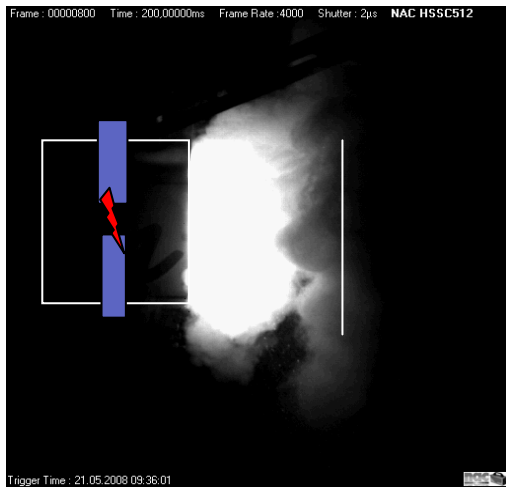
Arc protection class	Test level $W_{LB P}$	Protection level $W_{LB \bar{a}}$	
1	158 kJ	$(1...2,4) \cdot \left(\frac{a}{300 \text{ mm}}\right)^2 \cdot 158 \text{ kJ}$	Basic protection
2	318 kJ	$(1...2,4) \cdot \left(\frac{a}{300 \text{ mm}}\right)^2 \cdot 318 \text{ kJ}$	Increased protection

The box test set-up provides “worst case” heat transmission conditions. The heat flux to the test sample is directed by means of the box surrounding the electrode arrangement (arc burning conditions). Heat is transmitted by radiation but, in addition, also by the hot plasma and gas clouds formed around the arc (see Fig. 2). There is a very narrow space around the electrode configuration causing a directed flow towards the test sample as well as amplifications due to reflection (directed arc). Furthermore, there are hot metal particles, splashes and vapor contributing to the thermal effects. Exothermal reactions resulting from melting and burning of the electrode material (mainly aluminum) increase the total heat energy emitted by the arc. The box test electric arc energy level  $W_{LBP}$  characterizes the maximum thermal exposures. PPE tested shows protection up to this level. The incident energy the PPE is tested for, represents the highest possible exposure that an electric arc with the arc energy  $W_{LBP}$  is likely to cause. Under box test conditions the transmission factor is  $k_T = 1$ . As shown by experimental investigations the transmission factor will change to about  $k_T = 2.4$  if there is an open arc causing a accordingly reduced heat transmission and exposure.

The test distance between arc and test sample is fixed with  $a = 300$  mm. Consequently, an electric arc energy  $W_{LBP}$  will maximum cause this incident energy what the PPE is tested for, in a distance of  $a = 300$  mm. For deviating distance and arc exposure conditions an equivalent arc energy may be defined, leading to the same direct exposure incident energy. It characterizes the PPE protective threshold level regarding electric arc energy for any actual exposure conditions deviating from the test ones:

$$W_{LB\bar{a}} = k_T \cdot \left(\frac{a}{300\text{mm}}\right)^2 \cdot W_{LBP}$$

The equivalent arc energy is that one where the protective effect of the PPE is still given for any exposure distance  $a$  and arc burning conditions. From experimental investigations the dependency of arc exposures is found to be approximately inversely proportional to the square of the distance  $a$ .



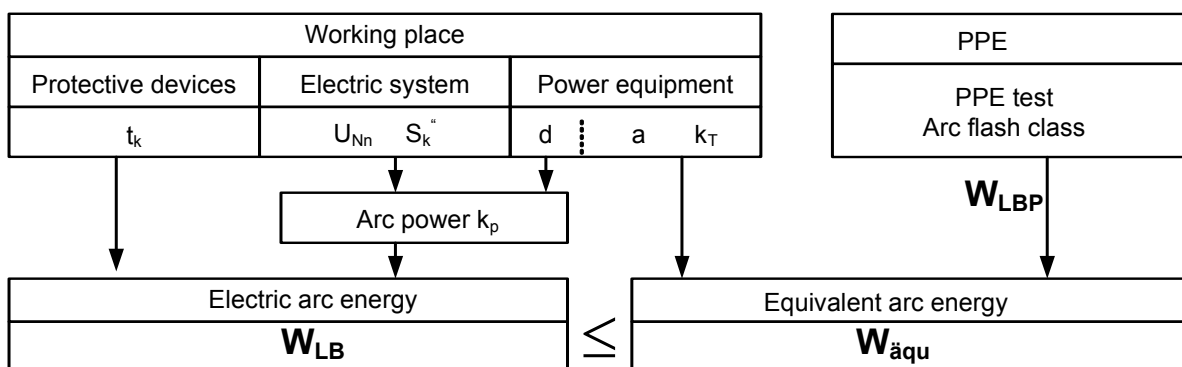
**Fig. 2:** Directed hot plasma and gas cloud (fire ball) resulting from the test arc in the box test

The factor  $k_T$  takes into account the electric power installation, particularly the volume of the opened compartment where the arc is expected to burn. As a standard and particularly for narrow constructions with side and back walls and low volume (house service boxes, distribution boards etc.) this factor is  $k_T = 1$ , for wider burning ranges (e.g. mainly back walls) it may be assumed as 1.5 to 1.9, and in case of open arcs as 2.4. The equivalent arc energy characterizes finally the resistance and protection threshold level of the PPE tested. It has to be compared with the expected arc energy. Personal protection is provided when

$$W_{LB} \leq W_{LBa}$$

### 4.3 Algorithm of risk analysis

The selection of PPE, or of the arc flash class for its testing, requires a risk analysis in which the electric arc energy to be expected in the work place(s) under consideration has to be determined as well as the equivalent arc energy characterizing the PPE protection level for the work activity conditions. Fig. 3 shows the procedure scheme summarizing the considerations made before.



**Fig. 3:** Overview on parameters and procedure for risk analysis in connection with box-tested PPE

## 5. Calculation examples and practical conclusions

By using the algorithm conclusions can be drawn regarding the application limits of PPE tested in the box test. Based on the box test arc energy levels the limits for the use of PPE of arc protection class 1 and class 2 were determined regarding the prospective short-circuit current (3-phase), the clearing time of the protective devices (arcing fault duration) and the working distance. Tab. 2 gives an overview.



**Tab. 2:** Application limits of PPE

Box test	Maximum prospective short-circuit current (3-phase)
Class 1	$I_{k3p}'' = \frac{91 \text{ kJ}}{U_N \cdot t_k \cdot k_P} \cdot \left(\frac{a}{300 \text{ mm}}\right)^2 \cdot (1...2,4)$
Class 2	$I_{k3p}'' = \frac{184 \text{ kJ}}{U_N \cdot t_k \cdot k_P} \cdot \left(\frac{a}{300 \text{ mm}}\right)^2 \cdot (1...2,4)$
	Maximum short-circuit duration (clearing time)
Class 1	$t_k = \frac{91 \text{ kJ}}{U_N \cdot I_{k3p}'' \cdot k_P} \cdot \left(\frac{a}{300 \text{ mm}}\right)^2 \cdot (1...2,4)$
Class 2	$t_k = \frac{184 \text{ kJ}}{U_N \cdot I_{k3p}'' \cdot k_P} \cdot \left(\frac{a}{300 \text{ mm}}\right)^2 \cdot (1...2,4)$
	Minimum working distance
Class 1	$a = 300 \text{ mm} \cdot \sqrt{\frac{k_P \cdot U_N \cdot I_{k3p}'' \cdot t_k}{(1...2,4) \cdot 91 \text{ kJ}}}$
Class 2	$a = 300 \text{ mm} \cdot \sqrt{\frac{k_P \cdot U_N \cdot I_{k3p}'' \cdot t_k}{(1...2,4) \cdot 184 \text{ kJ}}}$

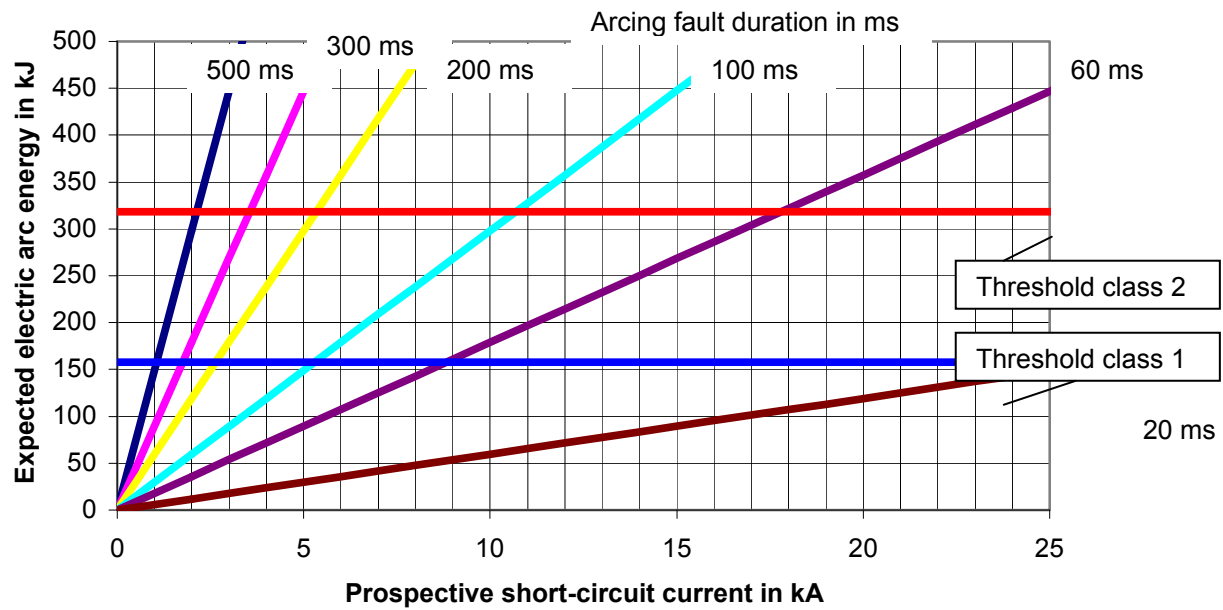
Bracket term (1...2,4) indicates the range resulting from the equipment volume conditions; standard value is 1 (characterizing low-space equipment construction)

An example is graphically analyzed in Fig. 4 and 5. Fig. 4 shows the arc energy expected in a 400 V system for varying prospective short-circuit current and different short-circuit duration. The calculation was based on a normalized arc power of  $k_P = 0.43$ . This is the maximum value resulting from Fig. 1 for an impedance ratio of  $R/X = 0.1$ . In LV systems  $R/X$  ratios are in general larger than 0.1, so that  $k_P$  does not exceed the value of 0.43. It is even significantly smaller in most cases. Consequently safety margins to real conditions are contained in the example. In the diagram the protection thresholds of arc protection class 1 and class 2 are indicated for a working distance of  $a = 300 \text{ mm}$  and standard equipment volume conditions ( $k_T = 1$ ). The crossing points of the threshold straights with the arc energy curves represent the limits up to which PPE of the tested class can be used and provide protection against the thermal hazards of electric fault arcs.

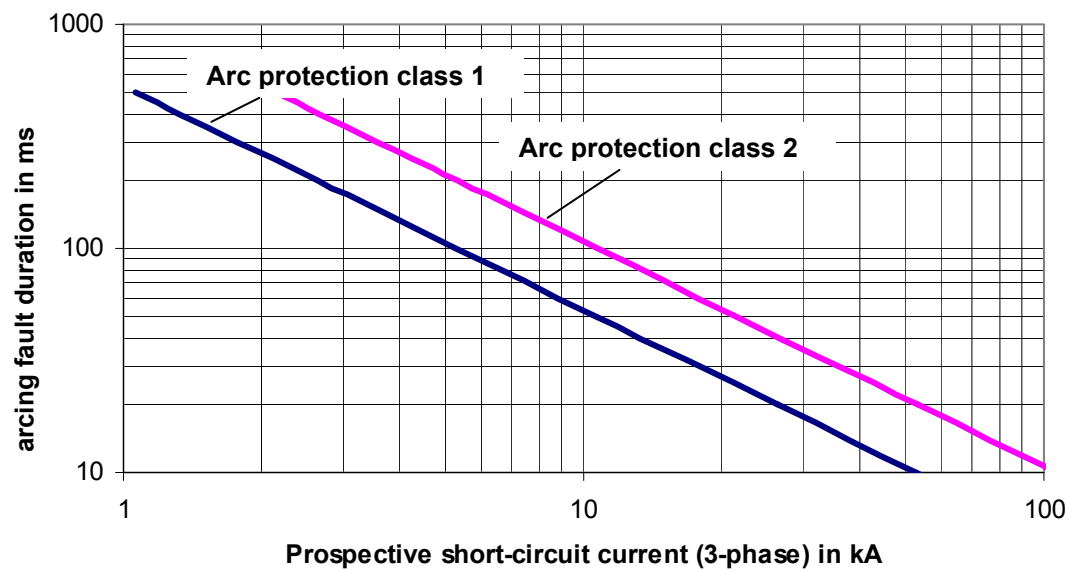
Thermal protection can be achieved for a given working environment by

- using PPE of the necessary class (or higher class)
- prescribing a minimum working distance to the risk zone
- limiting or reducing the clearing time of the protective devices.

If the relation  $W_{LB} \leq W_{LBa}$  could not be met, live working or working near to live parts is not permitted in the case concerned.



**Fig. 4:** Expected arc energy in dependency on prospective short-circuit current and arcing fault duration for a 400 V system under the assumption of  $k_p = 0.43$



**Fig. 5:** Application limits of arc protection classes for the example above and standard exposure conditions ( $a = 300 \text{ mm}$ ,  $k_T = 1$ )

Fig. 5 shows the arc protection class limits with respect to the relationship of the prospective short-circuit current and the arcing fault duration for the example conditions considered already before (400 V system, normalized arc power  $k_p = 0.43$ , standard working distance of  $a = 300 \text{ mm}$ , low-space equipment with  $k_T = 1$ ). In order to provide arc thermal protection by means of the PPE the curve of the class concerned may not be exceeded.

In general, the permission to extrapolate or transform the relationships to any parameter ranges (current, time) is limited because the non-linear dependencies actually existing are not considered in the simple relationships and extrapolations. This mainly applies to cases of extreme parameter values (extremely high currents, very short time durations).

On the other hand, worst case considerations as made generally and in the examples, can lead to larger differences to the actual conditions. However, the results are aimed to be on the safe side.

The risk analysis and assessment as described before is oriented to the use of PPE tested and classified in the box test (IEC or EN 61482-1-2 [1]). It cannot be directly applied, in a common way, when PPE is tested by another method (other set-up, heat transmission mechanisms). In the box test there are worst case heat transmission conditions allowing the arc energy box test level (or the equivalent arc energy) to be used as threshold of arc resistance and protection.

Also the ATPV resulting from tests according to IEC 61482-1-1 cannot be correlated to the arc energy thresholds  $W_{LBP}$  or  $W_{LBa}$  since the heat transmission and exposure conditions are different, and mathematical transformations are not possible.

The limits of PPE application are significantly influenced by the electric protective devices since the expected electric arc energy is determined by the arcing fault clearing time. There are different ways to ensure or also extend the PPE application range. Besides to the selection of short-circuit protective devices of short clearing time (tripping time and/or delay of release), it is possible to use extra devices such as “work protective fuses” (reduced rated current and rapid current-time characteristic) installed in the electric branches where the working activities take place while working. Another solution are special ultra-fast acting protective systems (arc detectors tripping shunting by short-circuiters, e.g. [12]) existing in the equipment (fixed-mounted) or temporary installed (mobile systems).

The clearing time of protective devices with current-depending characteristic is influenced by the short-circuit current attenuation effect by the fault arcs in LV systems. Fault arcs can cause significant attenuations (to 50...80 % of the prospective currents occasionally [10]). The current attenuation has to be taken into account when the arcing fault duration  $t_k$  is determined in the risk analysis and considered for PPE application. The actual arcing fault current can only approximately be calculated by empirical approaches and statistical considerations. From this point of view, special protective devices based on non-current depending tripping have advantages.

## 6. Summary

Electric fault arcs are of potential risk for the injury of persons working at electrical power installations, particularly when there is the danger of a direct exposure as in case of live working or working in the vicinity of live parts. Personal Protective Equipment (PPE) is able and must essentially contribute to the necessary protection.

For selecting protective measures such as PPE the electric arc energy parameters to be expected in the working places under consideration have to be determined and compared with target levels resulting from the equipment arc resistance and protective effect.

The determination of the arc energy parameters is not simple. There are occasionally large application ranges to be covered, much different electric system conditions, very various switchgear and power installation constructions, very different types and settings of the short-circuit protection devices (tripping times) etc. Furthermore the electric fault arc is a thermodynamic system and of stochastic nature. The heat transmission conditions are still more variant and hardly predictable. By means of empirical considerations based on a large number of power lab measurements and fault evaluations an approach of determination is presented and used. It allows to find expected arc exposures with a certain accuracy and probability. The risk analysis and assessment may be based on it. It is oriented to the use of PPE tested according to the box test.

The risk analysis algorithm allows to assess the suitability of PPE tested for the considered case. Furthermore PPE application ranges regarding practical parameters such as prospective short-circuit current and arcing fault duration can be derived, and conclusions drawn on how to achieve personal protection in a certain application.

The harmonized box test standard IEC or EN 61482-1-2 is directed to the textile material and protective clothing against the thermal hazards of an electric arc. Also protective gloves and face shields (visors) belong to PPE relevant for arc protection. As long as special product standards with defined requirements regarding arcing flash protection are missing, PPE should meet at least arc protection class 1 always if there is the risk of an exposure to a fault arc while working (electro-technical work), and be tested in accordance to the box test (with necessary modifications regarding sample holders etc.).

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